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THE FUNDAMENTAL PLANE OF FIELD EARLY TYPE GALAXIES AT $Z = 1$[1]

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ABSTRACT

We present deep VLT spectra of early type galaxies at $z \approx 1$ in the Chandra Deep Field South, from which we derive velocity dispersions. Together with structural parameters from Hubble Space Telescope imaging, we can study the Fundamental Plane for field early type galaxies at that epoch. We determine accurate mass-to-light ratios and colors for four field early type galaxies in the redshift range $0.96 < z < 1.14$, and two with $0.65 < z < 0.70$.

The galaxies were selected by color and morphology, and have generally red colors. Their velocity dispersions show, however, that they have a considerable spread in mass-to-light ratios (factor of 3). We find that the colors and directly measured mass-to-light ratios correlate well, demonstrating that the spread in mass-to-light ratios is real and reflects variations in stellar populations.

The most massive galaxies have mass-to-light ratios comparable to massive cluster galaxies at similar redshift, and therefore have stellar populations which formed at high redshift ($z > 2$). The lower mass galaxies at $z \approx 1$ have a lower average mass-to-light ratio, and one is a genuine 'E+A' galaxy. The mass-to-light ratios indicate that their luminosity weighted ages are a factor of three younger at the epoch of observation, due to either a late formation redshift, or due to late bursts of star formation contributing 20 - 30% of the mass.

Subject headings: cosmology: observations—galaxies: evolution—galaxies: formation

1. INTRODUCTION

The formation and evolution of early type galaxies is one of the major challenges for current structure formation models. Models of hierarchical structure generally predict that field early type galaxies form relatively late (e.g., Diaferio et al. 2001).

One of the prime diagnostics of the formation history of early type galaxies is the evolution of the mass-to-light ratio as measured from the Fundamental Plane (Franx 1993).

Studies of the evolution of the luminosity function together with the evolution of M/L quantifies the evolution of the mass function.

Previous studies of the evolution of mass-to-light ratios have produced consistent results for the evolution of massive cluster early type galaxies: the evolution is slow, consistent with star formation redshifts $z \approx 2$ (e.g., van Dokkum & Stanford 2003).

On the other hand, studies of the evolution of field galaxies have yielded more contradictory results: whereas early studies produced slow evolution (e.g., van Dokkum et al. 2001; Treu et al. 2002; Kochanek et al. 2000), more recently evidence for much faster evolution was found by Treu et al. (2002) and Gebhardt et al. (2003), whereas other authors found that the majority of field early types evolve slowly, with a relatively small fraction of fast evolving galaxies (e.g., Rusin et al. 2003; van Dokkum & Ellis 2003; van de Ven, van Dokkum, & Franx 2003; Bell et al. 2003).

These previous measurements suffered from several uncertainties: The signal-to-noise ratios of the spectra were generally quite low, much lower than usual for nearby studies of the FP (e.g., Faber et al. 1989; Jørgensen, Franx, & Kjærgaard 1996).

Those studies based on lensing galaxies used stellar velocity dispersions derived from image separations.

In this *Letter*, we present high signal-to-noise spectra and accurate measurements of the mass-to-light ratios of four elliptical field galaxies around redshift one and up to $z = 1.14$ and two at $z \sim 0.7$ in the Chandra Deep Field South (CDFS). The signal-to-noise ratios are comparable to those obtained for nearby galaxies. Together with accurate multi-band photometry available for the CDFS, we have measured the accurate mass-to-light ratios and rest frame optical colors at $z \sim 1$.

Throughout this *Letter* we use Vega magnitudes, and assume a Λ-dominated cosmology ($(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$), with a Hubble constant of $H_0 = 70\ km\ s^{-1}\ Mpc^{-1}$.

2. SPECTROSCOPY

2.1. *Sample selection and Observations*

The galaxies were selected from the COMBO17 catalogue (see Wolf et al. 2003), and imaging obtained by the Great Observatories Origin Deep Survey (GOODS[5], data release v0.5) from the Advanced Camera for Surveys (ACS) on the *Hubble Space Telescope*. We selected compact, regularly shaped galaxies with photometric redshifts higher than 0.8 and $I - z \geq (I - z)_{Sbc},\ z < 22$. $(I - z)_{Sbc}$ denotes the color of the Sbc template of (Coleman, Wu, & Weedman 1980) at the photometric redshift. This template has $(U - V)_{z=0} = 0.95$. The typical uncertainty in the color is 0.1 mag. Lower priority galaxies were included with either lower redshifts or later types.

The CDFS was observed in MXU-mode with the Focal Reducer/Low Dispersion Spectrograph 2 (FORS2) on the Very Large Telescope (VLT) Unit Telescope 4 during 3 runs from 2002 September through 2003 Februari, for a total of 14 hours. The 600z grism (central wavelength 9010Å, resolution 5.1Å or $\sigma_{instr} = 72\ km\ s^{-1}$) was used. During the observations towards the CDFS the seeing varied between 0.″7 and 1.″5, with a median seeing of about 1″. The sky was clear all the time.

[1] Based on observations collected at the European Southern Observatory, Chile (169.A-0458).

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[5] http://www.stsci.edu/science/goods/

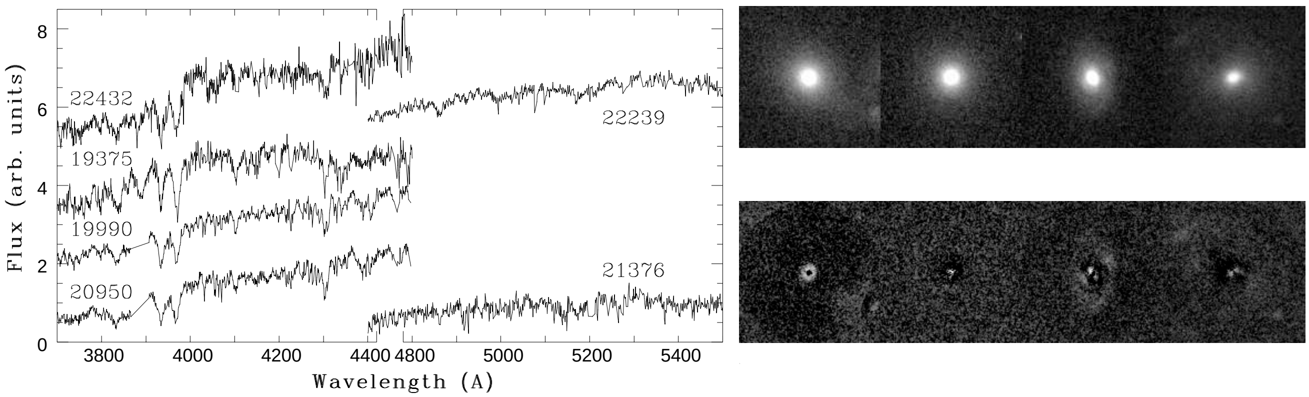

FIG. 1.— Left panel: unsmoothed restframe spectra of the siz objects with velocity dispersions. Regions with bright sky lines are interpolated. The wavelength scale is interrupted at λ = 4500Å. Right panel: ACS images (F850LP) of the four galaxies at $z \sim 1$ and the residual images from the $r^{1/4}$-fit. From left to right: 20950, 19990, 19375, 22432.

2.2. *Velocity Dispersions*

It turned out that 10 out of the 11 high priority objects at $z_{phot} \sim 1$ have the spectrum of a quiescent galaxy, the other one has a bright [O II] emission line. The brightest four ($z \lesssim 21.0$, independent of the color) had sufficient signal-to-noise ratios to perform reliable dispersion measurements (see Table 1). The restframe spectra of these 4 galaxies are shown in Figure 1. They all show a strong 4000Å-break and Ca-lines. Balmer lines (especially the $H\delta$-line) are also present, though varying in strength from object to object (see Table 1). Object 19375 is an 'E+A' galaxy, according to the criteria used by Fisher et al. (1998). For 2 ellipticals with $0.65 < z < 0.70$ we also have sufficient signal to determine a velocity dispersion.

Dispersions were measured by convolving a template star spectrum to fit the galaxy spectrum as outlined by van Dokkum & Franx (1996). We tested this procedure extensively, using different template stars and masking various spectral regions. The final values (see Table 1) for the velocity dispersions were obtained by masking the Ca H and K and Balmer lines and using the best fitting template spectrum, which was a high-resolution solar model spectrum[6] smoothed and rebinned to match the resolution of the galaxy spectra. The Ca-lines were not included in the fit because this greatly reduced the dependence of the measured velocity dispersions on template type. The tests using different templates and different masking of the Ca lines indicate that the systematic uncertainty is $\sim 5\%$.

In order for the results to be comparable to previous studies, an aperture correction as described by Jørgensen, Franx, & Kjærgaard (1995b) was applied to obtain velocity dispersions within a circular aperture with a radius of 1.″7 at the distance of the Coma cluster. This correction is $\sim 7\%$.

This is the first extensive sample of such objects at $z > 0.9$ with high S/N. (see van Dokkum & Ellis 2003; Treu et al. 2002; Gebhardt et al. 2003 for other spectroscopic studies).

3. PHOTOMETRY

Photometry and structural parameters were determined from the GOODS ACS images (data release v1.0). Images are available in 4 filters (F435W, F606W, F775W, F850LP), which we refer to as b, v, i, and z, respectively.

For each object, the effective radius (r_e) and the surface brightness at the effective radius (μ_e) were obtained by fitting an $r^{1/4}$-profile, convolved by the PSF (van Dokkum & Franx 1996). z-band images were used for the $z \sim 1$ objects and i-band images for the $z \sim 0.7$ objects. Stars were used as the PSF. The resulting values for r_e and μ_e vary by $\approx 10\%$ when using different stars, but also correlate such that the error is almost parallel to the FP (van Dokkum & Franx 1996). Therefore, the errors in our results are dominated by the errors in the velocity dispersions. The results are listed in Table 1. The images of the $z \sim 1$ objects and the residuals of the fits are shown in Figure 1.

To determine the $i-z$ and $v-i$ colors, fluxes were calculated from the $r^{1/4}$-model within the measured effective radius. To this model flux we add the flux within the same radius in the residual images. We corrected for galactic extinction based on the extinction maps from Schlegel, Finkbeiner, & Davis (1998). The correction is extremely small: $E(B-V) = 0.007$.

Restframe B-band surface brightnesses and restframe $U-V$ colors were obtained by transforming observed flux densities in two filters to a restframe flux density exactly as outlined by van Dokkum & Franx (1996). The spectral energy distribution used to calculate the transformations is the early type spectrum from Coleman et al. (1980). We found the same results for other template spectra. The results are listed in Table 1.

4. MASS-TO-LIGHT RATIOS FROM THE FP

Figure 2a shows the FP for the 6 field galaxies described above, and the FP for Coma derived by Jørgensen et al. (1996). Additionally, we show the results from van Dokkum & Stanford (2003) on three cluster galaxies at $z = 1.27$. The offsets of the high redshift galaxies from the Coma FP are a measure of the evolution of M/L. We show the evolution of M/L in Figure 2b as a function of redshift.

Obviously, the field galaxies at $z > 0.6$ span a wide range in offsets, approximately a factor of 3 in M/L. The errorbars on the individual points are much smaller than the offsets. A model with a single formation redshift can be ruled out at the 99% confidence level, as measured from the χ^2-method. The restframe

[6] http://bass2000.obspm.fr

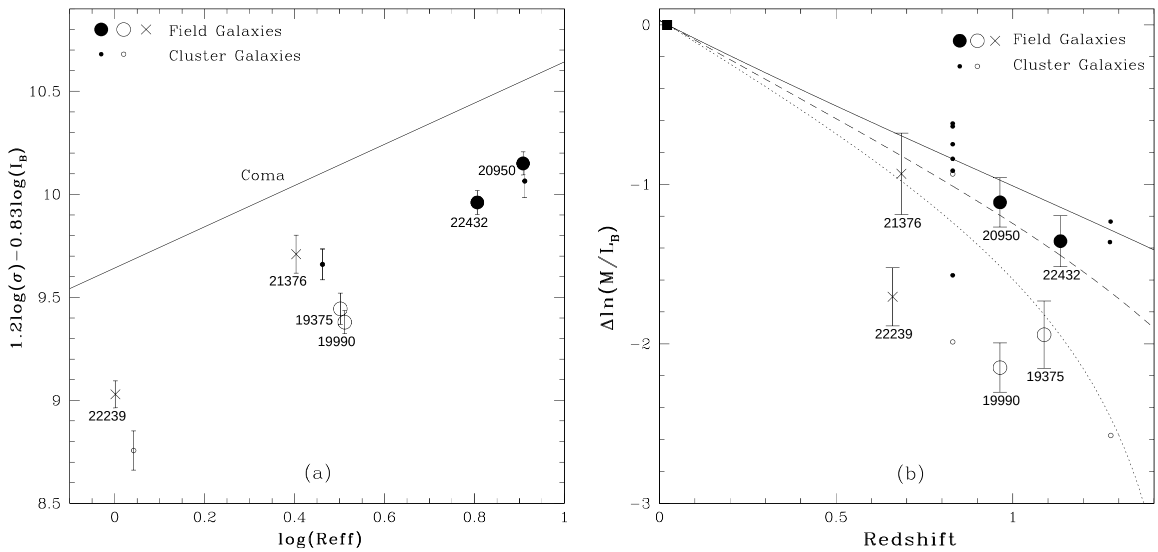

FIG. 2.— Figure 2a shows the FP points of the field galaxies presented in this paper (errors include a 5% systematic effect in the velocity dispersions), the FP points of cluster galaxies at $z = 1.27$ (van Dokkum & Standford 2003), and the FP of the Coma cluster (Jørgensen et al. 1996). Offsets in M/L_B from the Coma cluster FP (the square, derived from Jørgensen et al. 1996) are shown in Figure 2b. Besides the $z = 1.27$-cluster, this figure also contains the data from van Dokkum et al. (1998) on the MS1054 cluster at $z = 0.83$. The full, dashed and dotted curves are the model predictions for a single burst of starformation with a Salpeter IMF for redshifts 3, 2, and 1.5, respectively. Filled symbols indicate galaxies with masses $M > 3\times10^{11}M_{\odot}$, other symbols indicate galaxies less massive than that. Crosses and squares distinguish between galaxies at $z < 0.8$ and $z > 0.8$, respectively. All galaxies occupying the region below the $z = 1.5$ model curve are 'E+A' galaxies, except 19990, and have masses less than $3\times10^{11}M_{\odot}$. The more massive galaxies have significantly older stellar populations.

colors of the galaxies confirm the reality of the variations in the mass-to-light ratios. As shown in Figure 3, a very strong correlation exists between the colors and the mass-to-light ratios in the direction expected from population sysnthesis models.

The good correlation demonstrates that colors can be used to estimate the mass-to-light ratios, as applied, for example, by Bell et al. (2003) to a large sample of field early type galaxies.

Note that galaxies in our study lie fairly close to the red sequence, and were characterised by Bell et al. (2003) to have red colors. The overall spread in colors of field galaxies is much larger (1.5 mag) compared to the spread found here (0.3 mag).

5. DISCUSSION

On the basis of our high signal-to-noise spectra we have found a rather wide range in M/L for early type galaxies at $z = 1$, indicating a range in star formation histories. The mass-to-light ratios and colors are well correlated, as predicted by stellar population models. Hence the scatter in M/L is real.

The results agree surprisingly well with earlier results based on lensing galaxies. Rusin et al. (2003) and van de Ven et al. (2003) found a range in M/L, and van de Ven et al. (2003) found a similar correlation between restframe colors, and M/L.

Other authors found either low mass-to-light ratios (e.g., Treu et al. 2002; Gebhardt et al. 2003), or high mass-to-light ratios (e.g., van Dokkum & Ellis 2003), and this is most likely due to (still unexplained) sample selection effects. The last authors found that galaxies with residuals from the $r^{1/4}$ profile had young ages. However, we find no such relation in our sample.

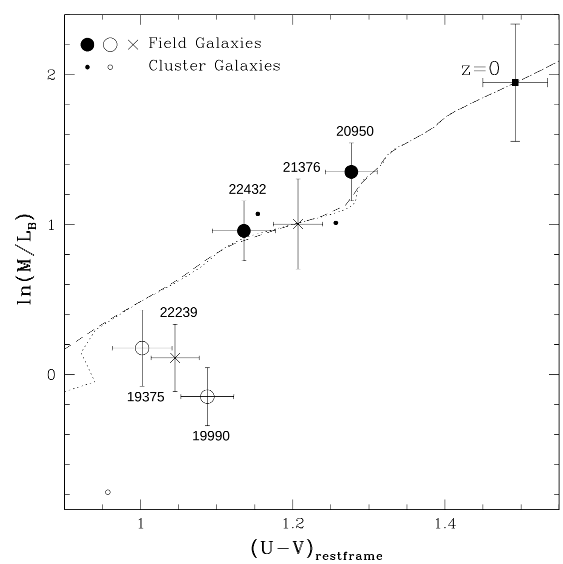

FIG. 3.— Restframe $U-V$ color versus M/L_B in solar units. Filled symbols are objects more massive than $M > 3\times10^{11}M_{\odot}$, open symbols represent the less massive ones. The cluster galaxies are the $z = 1.27$-galaxies from Figure 2. The redshift zero datapoint is the average for galaxies with $\sigma > 150$ $km\ s^{-1}$ in the clusters Abell 194 and DC2345-28 (Jørgensen, Franx, & Kjærgaard 1995a). The lines are solar metallicity Bruzual & Charlot (2003) models with constant star formation during the first 200 *Myr* (dotted) and exponentially decaying star formation on the same time scale (dashed).

TABLE 1
PHOTOMETRIC AND SPECTROSCOPIC PROPERTIES

ID	α	δ	z_{spec}	i	$v-i$	$i-z$	log(r_e)	μ_e	S/N	σ	(Hγ+Hδ)/2	[O II]
	$''$	$''$					(kpc)		(Å^{-1})	(km/s)	(Å)	(Å)
19375	0	-50	1.089	21.72	1.71	1.04	-0.410±0.012	21.75±0.05	26	198±25	4.1	-4.6
19990	-32	-35	0.964	21.32	1.89	1.00	-0.388±0.007	21.45±0.03	49	159±14	2.5	>-1
20950	-73	-6	0.964	21.18	2.07	1.07	0.0085±0.026	22.95±0.08	39	261±23	<1	>-1
22432	83	41	1.135	22.38	2.00	1.42	-0.109±0.040	23.35±0.13	21	217±20	<1	-4.4
21376	129	10	0.685	21.46	1.77	0.58	-0.447±0.001	22.16±0.04	27	156±24	–	–
22239	236	35	0.660	20.67	1.67	0.50	-0.842±0.002	19.83±0.03	40	177±19	–	–

Note. — Coordinates are in in arcseconds east and north of RA= $03^h32^m25^s$, Dec= $-27^\circ54'00''$. Errors in the magnitudes and colors are, respectively, 0.03 and 0.05 mag. Effective radii and surface brightnesses ($mag/arcsec^2$ at r_e) are measured in the z-band for objects 19375, 19990, 20950 and 22432, and in the i-band for objects 21376 and 22239. The listed errors in the velocity dispersions are fitting errors, and do not include a 5% systematic error.

Stellar population models indicate that the low mass-to-light ratios of the blue $z \approx 1$ galaxies may be due to an age difference of a factor of three. Alternatively, bursts involving 20-30 % of the mass can produce similar offsets. The current sample is too small to determine the fraction of young early type galaxies at $z \approx 1$ reliably. Large, mass selected samples are needed for this, as current samples are generally optically selected, and therefore biased towards galaxies with lower mass-to-light ratios.

It is striking that the most massive galaxies have modest evolution in M/L, similar to what van Dokkum & Stanford (2003) found for massive cluster galaxies. The evolution of the galaxies with $M = 6.07\ r_e\sigma^2 \geq 3\times10^{11}M_\odot$ (Jørgensen et al. 1996) in our sample is $\Delta\ln M/L_B = -1.17\pm0.14\ z$. The mass limit is comparable to the M_* mass of an early type galaxy: if we take the σ_* of early type galaxies derived by Kochanek (1994) of 225 km/s, we derive a typical mass of $M_* = 3.1\times10^{11}M_\odot$ based on the sample measured by Faber et al. (1989). The sample as a whole evolves as $\Delta\ln M/L_B = -1.64\pm0.45\,z$, whereas the sample with masses smaller than $3\times10^{11}M_\odot$ evolves as $\Delta\ln M/L_B = -1.95\pm0.29\,z$.

The results are therefore consistent with little or no (recent) starformation in massive early type galaxies out to $z = 1$, and younger populations in less massive galaxies, possibly caused by bursts involving up to 30% of the stellar mass. Since these less massive galaxies have much more regular stellar populations at $z < 0.5$ without signs of recent star formation, these results are consistent with the downsizing seen in the field population (Cowie et al. 1996): at progressively higher redshifts, more and more massive galaxies are undergoing strong star formation.

It remains to be seen how this trend continues out to even higher redshifts. The biases inherent in studies of galaxies at $z = 2$ and higher make it very hard to perform similar studies: the optical light has shifted to the near-IR, and spectroscopy is extremely hard at those wavelengths.

More studies at redshift $z \approx 1$ are needed to determine the distribution of colors and mass-to-light ratios of the progenitors of field early types. Such a determination should be based on mass-selected samples. Further studies of spectral energy distributions extending to the restframe infrared will be very useful to constrain the star formation histories of the bluer galaxies better.

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